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NON-DESTRUCTIVE TESTING.

By Dr. HORACE MANLEY.

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NON-DESTRUCTIVE TESTING

by DR. HORACE MANLEY.

INTRODUCTION.

UNTIL the last two decades or just a little longer there has been only one way of determining whether a manufactured metal product—forging, casting, billet, turning or sheet, is mechanically sound—to test to destruction. Almost the only useful scientific application of these tests (tensile, shear, izod, impact, etc.) is where statistical mathematics can be applied on the untested specimens. A small sample, say 2% or 5% of the batch of castings can be tested to destruction. If the sample is sufficiently large and typical enough, then the number of failures below specification in the test set allows a reasonably accurate prediction of the number of sub-standard units in the production batch.

Such methods are not suitable for large, single, expensive or vital pieces of equipment where one requires, ideally, a 100% guarantee, *e.g.*, aircraft components. Further, many causes of structural failure develop in service and one would prefer to be able to apply some test after, say, 100 or 1000 hours' service. A test method which destroys the specimen is, then, clearly undesirable, and in practice of very restricted utility.

The only common non-destructive test of any long standing is hardness—a useful tool for estimating heat treatment efficiency and tensile strength, but little more. Hardness testing itself has, of course, rapidly expanded in its applications and variety of equipment in the last twenty years. There are several standard text-books on hardness testing and since it is not usually considered as coming within the restricted field of non-destructive testing it will not be considered in any detail.

Largely since 1930 a group of methods have developed for detecting cracks of all types, segregation, piping, inclusions, porosity, etc., inside large metal components. These methods, which mostly depend on not too obvious physical properties, usually can be made into portable equipment. They leave the object tested in almost precisely the same state after completion of test as before and due to this latter fact, combined with a high sensitivity, they have met with wide acceptance. The methods are known by the generic term "non-destructive tests"—which will be abbreviated 'n.d.t.' in the text.

It is probably best to stress that these methods are most widely used for surface and sub-surface crack detection, although the other types of flaws can be, and are, found. Doubtless this stress on crack detection is partly a reflection on the frequency with which mechanical failure is due to the sudden enlargement of a crack, either an original defect in the casting, etc., or a fatigue crack born of service. The methods used to-day are—the use of fluorescent inks, liquids and paints, a variety of magnetic techniques, the ultrasonic devices and radiography with X and gamma rays.

Each of these methods will be considered in turn in a separate chapter with a brief outline of historical methods. The main advantages and shortcomings will be pointed out but it will be appreciated that practical advances and variations are being made in each branch all the while. Hence the various commercial equipments vary in detailed tactics from firm to firm, from country to country, and as the particular problems require. There has been a strong "fashion complex" in the different countries leading to the extreme developments of one technique to the exclusion of others which are simpler or easier, in different countries, but this is slowly dying away.

The term "non-destructive testing" is, again, taken in its more narrow meaning, as most usually applied, *i.e.*, referring only to metals, although some mention will be made of related applications —for instance radiography to check inserts in plastic equipment. A few extremely specialised techniques do exist for other substances, *e.g.*, photo-elasticity for some transparent plastics, and special fluorescent crack detection methods for glass, but by and large these are considered outside the scope of this booklet.

CHAPTER 1.

FLUORESCENT METHODS.

It has been suggested that non-destructive testing as a branch of applied science or engineering has only existed twenty or thirty years. There were a variety of more or less successful methods for detecting gross surface cracks, however, used in some fitting shops, foundries, etc., for generations. These "chalk dust type" tests are rarely used by large firms to-day, as fluorescent inks and paints which have replaced them and, indeed, extended the field of utility, are readily available, more sensitive, and uniform in quality.

Cracks have been the bane of metalworkers for centuries and no one can now be certain when it was first realised that surface cracks could cause structural failures. Large cracks on a clean, well-lit surface are easily seen. Smaller ones may be detected by special illumination such as a brighter, more diffuse lamp or holding the surface at an appropriate angle with respect to the light source and eye.

These cracks stand out more clearly when they trap oil inside themselves during storage or the various machining operations. Dirt and dust may adhere to the oil and just round the edge of the crack, which then becomes obvious to the eye as a smudgy or greasy line. Chalk dust being white aids vision and could be deliberately sprinkled over the surface and then wiped off, when it would remain only in any cracks and flaws. Clearly the use of an oil, deliberately put on the metal surface, of low surface tension and viscosity, combined with the addition of chalk dust, leads to a primitive form of crack detection. Small cracks which might be completely missed in a normal inspection will be more certainly detected, especially when the viewer is somewhat fatigued. Presumably the development of this trapped oil method of crack detection began from acute observation aided by such simple materials as might be commonly available in a foundry or machine shop—oil or paraffin and some white powder.

Clearly there are several variations of this crude method of surface flaw detection. Some would prefer a "dry" technique—brushing fine chalk or talc dust over the area of metal to be tested and then blowing or dusting off the powder, again, so that a white line would be seen where the fine particles were caught in the hollow of the crack or flaw. This idea is improved by using powders of optimum particle size, consistency and hardness.

In the "wet" methods the chalk or talc will be mixed with paraffin or other oils to give a suitable viscosity, surface tension and general consistency. For small test objects one technique is to stew the part in paraffin oil with just a trace of some thin oil, for about 30 minutes at, say, 70°C. After removal from the liquid they are allowed to cool and then thoroughly wiped dry. When French chalk is dusted over the samples it adheres to any oil in blowholes, porous portions, cracks, etc. For small objects the surface can be wiped clean when the defects will stand out from the white mess in them. For large objects such as billets, a variation in technique can be employed. Being so large they store a great deal of heat, and if the powder is dusted on them before they are completely dry, then the oil will be squeezed out from the defect by the contraction of the metal—and regions containing defects will appear as wet lines or blotches—so much oil will be extruded that quite a little region around the flaw will be completely wetted and cause the powder to "run."

A slightly different and more advanced technique is as follows. The sample is oiled all over. It is then cleaned with meths. and a "thinners" liquid applied. This liquid may contain 25% chalk and a small amount of red dye which is insoluble in the oil first applied. The thinners in the liquid quickly evaporates after its application and leaves the chalk behind on the surface. The chalk absorbs any oil in any defect and, the dye chosen being insoluble in oil, comes out of solution. In appearance, then, a crack will be white—due to chalk and oil, with a red mark round it due to the dye. Obviously this technique makes detection easier and more noticeable, and can be applied as a routine test to an engine cylinder for example, where one does not wish to strip down the entire set up.

In these wet methods the liquids are usually a paraffin base if they operate at a lowish temperature, say, 25°C., but carbon tetrachloride if they operate at a higher temperature. Red lead and other bright powders have been used in place of talc or chalk.

A rather different and less universal method is the "acid etch." This has the advantage of providing a mat background giving greater contrast. A typical procedure will be to immerse the component in the etch solution for some known time, remove it, dry it and then inspect. It is suitable for most metals given an appropriate etching agent, but has usually been restricted to non-ferrous or non-magnetic alloys—such as stainless steel. Since the dull surface is produced at the expense of slight surface attack the component must be thoroughly greased after the test to prevent corrosion. Also, in general one will apply the test before the product is completed, especially when dimensional accuracy or an unpainted surface is required. A special use of the acid etch method, in certain cases, is the detection of burning by bad grinding.

Suggested etching solutions include—5% nitric acid in water or methylated spirits for mild steel, with an immersion time of 1½ minutes. For aluminium alloys two solutions are best—an etch with 10% sulphuric acid containing 1% sodium fluoride, followed, after washing in water, by 50% nitric acid. The reason for the two solutions lies in the fact that the etch acid leaves the surface dirty, the nitric acid cleaning it. This dirty surface is left by sulphuric acid solutions when cleaning most metal surfaces, *e.g.*, copper alloys. Using this technique for aluminium alloys it is suggested that the best results obtain if inspection is delayed about half an hour after treatment. For stainless steels a strong acid is recommended, for instance 50% hydrochloric acid at 70°C. for 5 minutes.

With the acid solutions mentioned the etched cracks appear as dark lines, usually inclusions are noteworthy as colour differences, and grinding burns appear darker than the background. For testing portions of finished materials the acids may be applied with a swab. As mentioned previously there is a natural preference to use the chalk powder methods on finished products as the acid ones are frequently undesirable and often impossible at a late stage in production.

Although the techniques mentioned above have been developed to a moderate degree, by and large they can be considered obsolete for most purposes. They have been superseded by the various direct fluorescent methods. Here suitable chemicals are dissolved in organic liquids and washed over the cleaned metal surface and then, after a time interval, removed. When the metal surface has dried the entrapped liquid in the cracks appears to bulge out over the surface and since the liquid is fluorescent it will glow intensely sometimes of its own accord, but more usually when viewed under ultra-violet light—the so-called "black light." Large cracks glow green or blue and even quite small ones glint and flash as one moves the lamp, the object, or one's head.

There is quite a choice of suitable liquids. Many natural oils are fluorescent and there are a few suitable solids, such as fluorescein, which glow brightly in normal light. More usually a liquid or solution is used which fluoresces under ultra-violet light. There are several advantages in this, amongst them the better control of intensity with a known ultra-violet lamp in a cabinet under constant conditions rather than variable daylight. Further, most naturally fluorescent substances are rather weak in light intensity, whereas under ultra-violet one gets extremely strong fluorescence.

Several commercially successful products are available, *e.g.*, "Hyglo" in England, "Zyglo" in U.S.A. It should be mentioned that care is necessary in cleaning the surfaces, partly because acids or alkalies usually "kill" the fluorescent compounds. Also, of course, great care must be used in designing the inspection cabinet to ensure that the operators are shielded from direct vision of the ultra-violet light source as the rays are most injurious to the eyes and skin. Before test, any oil, scale, acids or alkalies on the test surface must be removed and it is good practice to sand blast welds.

The "Zyglo" method contains two liquids. The clean surface is coated with a water washable fluorescent liquid and twenty minutes allowed for penetration, after which the liquid is washed off with water.. Then a wet "developer" is added—a liquid of low surface tension which pulls out the fluorescent one trapped in the flaws. After drying, the surface is inspected under an ultra-violet lamp. The method is quite widely used for all types of non-magnetic material—it can be used on magnetic surfaces as well, of course, but usually is not. Typical successful uses are in inspection of valve and roller axle bearing retainers made of non-magnetic nickel-chrome alloys. It may not work if the cracks happen to be grease-filled and have not been well cleaned with a grease solvent. It is very good for detecting grinding cracks and heat cracks on diesel valves.

Perhaps one should mention here, that we are not concerned with the fluorescent liquids sometimes used as an aid in magnetic particle inspection—that method being primarily magnetic—nor with the use of fluorescent screens, which will be mentioned later in connection with mass production radiography, which are gamma or X-ray inspection methods, in the main using principles of fluorescence as an auxiliary.

The direct fluorescent liquids have the advantage of universal application, lack of corrosive liquids, rather easy procedure and a good commercially available cheap source of supply. By suitable arrangement of the distance of the specimen from observer some form of useful "go, no-go" limits on crack sizes can be set. It has become increasingly important to realise that with the rather sensitive modern methods of testing, very small flaws may be found which are insignificant for the purposes to hand and clearly needless rejection of suitable material is on a par with passing faulty production. So that if only major defects need to be noted it is advisable to adjust the sensitivity of the device used to the individual requirements, in this case by appropriate distance relationships in inspection.

These sorts of fluorescent tests are such that unskilled girl operators can usually be trained for the job in a day or so. Being optical methods depending on the physical inclusion of material in the flaw detected, clearly they only work for flaws which outcrop at the surface. They are entirely surface methods.

CHAPTER 2.

MAGNETIC METHODS.

As early as 1922 a gauge block manufacturer noticed that very fine particles tended to stick round the grinding cracks in some steels. Presumably these steels obtained a small permanent magnetisation during manufacture, as scissors sometimes do, and fine iron dust was attracted to the strong free poles where the magnetic field was obstructed by cracks and discontinuities in the metal surface. The magnetic method slowly developed and was for some years the only current n.d.t. method used in industry.

Most soft irons and steels do not retain magnetism although they can become temporary magnets when placed in a strong field. The ways of obtaining the magnetic field have roughly followed the same history as the techniques used in academic study. At first the specimen would be placed between the poles of existing permanent magnets. As the sensitivity was not high due to the low field strengths obtained, and also with the disadvantages and general clumsiness of the method, electromagnets were then used and now have a monopoly due to their flexibility and greater power and hence increased sensitivity.

There was also the problem of the detector, in the early days just iron and steel grindings or filings. However by 1929 a uniform graded powder of iron oxide particles was available, being widely used to-day. This oxide is usually black but was made in a brown form also, to give greater contrast against the steel or iron background of the test sample. Then the powder was suspended in a light oil and, more recently, aluminium dust has been added, giving a white powder of good contrast. Also fluorescent liquids have been used, introduced in 1942, in effect combining the magnetic and direct fluorescent methods. When dry powder is used it is called the "dry" method, when the powder is suspended in a liquid it is called "wet."

Magnetic particles collect around free poles formed by the crack or defect. These free poles only occur if the crack is more or less perpendicular to the direction of magnetisation, so that when using a permanent magnet to provide the field one will normally only detect those cracks lying nearly across the longitudinal magnetisation. One of the advantages of introducing electromagnetic techniques was that circular polarisation could be obtained and hence longitudinal cracks could be detected in, say, a pipe or rod. There are many forms of electro-magnets available. If the sample is a pipe or any object with symmetry and a hole through its centre a coil of wire can be wound round it and current passed through it to generate the required field. In some cases the current may be passed through the sample itself if it is solid, say, a crank case or shaft. Also, on occasions, the current can be passed through just a small portion of the specimen by attached leads to either end of the test section and passing current through it. Some of these methods are indicated in the sketch, with the types of crack they best detect. A further variable is the fact that either D.C. or A.C. may be used. These various methods are illustrated in the diagram Fig. 1.

An early application of magnetic particle testing was for finding grinding cracks, for which it is excellent, and for detecting fatigue cracks developed during service—for example on axles of trains, rolling stock, coaches, etc. Later by refinement and applying experience, stringers and seam defects in wire and bar stock could be detected. Initially, magnetic methods were intended solely for surface flaw detection but they have been applied to defects up to half-an-inch or more below the surface. As would be expected from the "skin effect" A.C. methods are less able to detect sub-surface faults than D.C. ones. In general, too, dry particles are rather more sensitive than the wet liquids.

A standard equipment is made in this country by Met-Vickers. "Electroflux" and "Periflux" were developed in Germany and "Magnaflux" and "Magnaglo" in U.S.A. A rapid drying collodion liquid has been used in Russia whereby a print can be obtained and kept of the magnetic pattern—rather similar to a sulphur etch print. When using liquids, of course, the particles tend to settle out being of density 5 (oxide) to 7 (metal powder) in a liquid of density only 0·9 (paraffin or light oil).

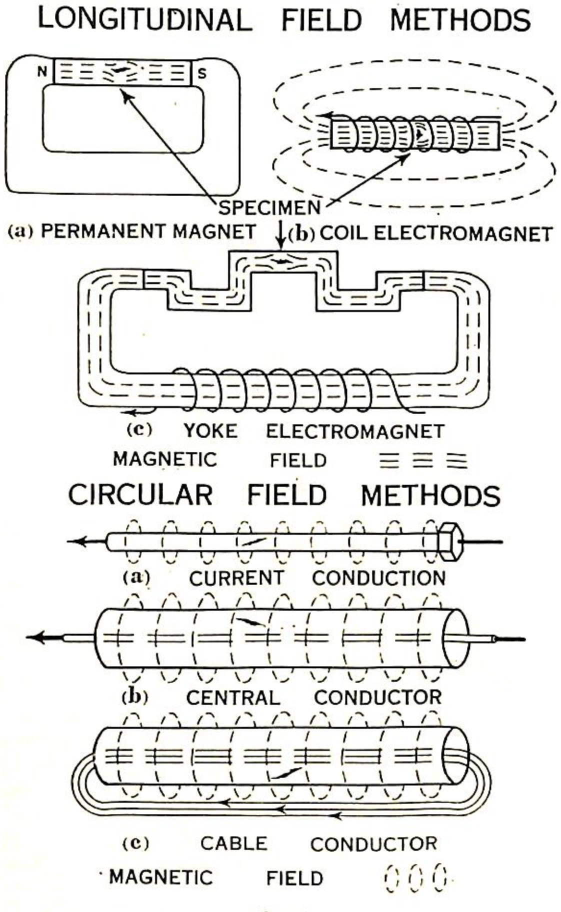


Fig. 1.

Maximum sensitivity can be obtained by using D.C. magnetising current and dry particles sprayed on with a powder gun or blower. This has been used for testing aircraft steel components and welds. As usual, one does not apply high sensitivity unless required because it may show up large numbers of insignificant defects. It is also a fact that although for years one major aim was to increase the magnetic field and hence the sensitivity, this can be offset by the fact that at very high magnetic fields the powder clots together and will actually greatly reduce sensitivity and not even show quite large cracks.

For the routine checks and maintenance overhaul on railways, etc., A.C. magnetising current is commonly used with wet suspensions. High currents at low voltages are used for both A.C. and D.C., frequently plating generators or welding rectifiers and equipment is found useful as a power source. Sometimes residual magnetic methods are used for small components which can then be inspected all at once on withdrawal from a bath of powder suspension, but few alloys retain magnetism and it can be a disadvantage in later machining operations.

A typical success of the magnetic particle techniques was in a case of hot tears running round the base flanges of valves which persistently leaked but passed radiographic and pressure tests. Cracks were shown to run circumferentially round these flanges, beneath the surface, in as many as 30% of the valves. Rudder post cracks is another naval application which had defied X-rays.

Of typical casting defects magnetic particle techniques are good for finding hot tears, most near-surface and surface cracks and unfused chaplets, but not centreline shrinkage, or dispersed slag and sand. Magnetic is quicker and cheaper than radiographic methods and very suited to mass production lines.

Other railroad pieces tested with magnetic particles include ring gears, dowel pin holes on engine rods and searching for fillet cracks on crank pins. Also several American companies inspect their running rails with cars running over them with rather specialised magnetic equipment. Laminations have also been detected in firebox plates, track welds and bolt hole areas in crossings.

To a lesser extent welds are inspected and also forgings, in this latter case the main idea being to prevent expense of machining and wasted labour on defective parts. For forgings, current densities as high as 1000/1200 amps. per sq. inch are used with dry powder if the surface is rough, as it has better colour contrast than the wet which may be used on very smooth surfaces. As early as 1920/22 H. Massey in England applied magnetic n.d.t. to show metal flaws in forgings.

Peculiar distinctive patterns can be obtained for rather unusual defects such as ineffective quenching of some forgings and a speckled band characteristic of burning or overheat. A definite advantage in the magnetic methods is that accepted standards now exist and most places use similar or the same type of commercial equipment. Some deep flaws can be found with welds and dry powder, cracks more than ½" deep, lack of fusion and incomplete penetration. Another speciality is the inspection of crane hooks for the cracks which tend to occur on the curve where the load is taken; D.C.

current through the hook is best. Large steel springs also respond well to this type of flaw detection.

There also exists a completely different form of magnetic n.d.t. called either magnetic analysis or magnetic sorting.

Magnetic Analysis.

In 1868 a Mr. Saxby detected defects in gun barrels by means of a compass ; in 1880 another scientist published a paper entitled "Can the magnetism of steels be used to determine their physical properties ? " To-day the answer is very definitely yes. The production figures of an American firm specialising in magnetic analysis show, for instance, that even pre-war they were testing very large quantities of bar stock. Production figures for successive years from 1932 to 1937 show a fortyfold increase. In 1932 2,000 tons were inspected, in 1933 8,000 tons, 21,000 in 1934, in 1935 46,000, rising to 63,000 in 1936 and 87,000 in 1937.

Initially the idea was that steels of different composition would have a different remanent magnetism, particularly after heat treatment. Then the D.C. permeability of turbine blades was used as a test of correct choice of metal and heat-treatment. Later, other aspects of the hysteresis curve have been used.

A common form of this type of n.d.t. is the magnetic sorting bridge developed so much during the war. It is particularly suited to mass production testing of small pieces, especially cylindrical, rod and bar forms and their derivatives. The production sample is put inside a test coil and compared electronically with a standard specimen inside an identical coil. Usually the detection is done on a cathode ray oscilloscope, giving good visibility and making it suitable for unskilled women operators.

When the samples are of the same steel, correctly heat-treated, the cathode ray tube shows a flat straight line, *i.e.*, sample and standard are identical. If the wrong metal, or incorrect annealing, tempering, etc., has been used an odd-shaped curve will be seen, its area approximately proportional to the fault or difference between specimens.

Apparatus exists with principles working on the permeability, incremental permeability, B-H loop, hysteresis loop area or shape, remanence, coercivity, etc., *i.e.*, all the different parts of the hysteresis curve. The equipments can test for structural uniformity, hardness, grain size, composition (say % carbon), strain or heat-treatment.

These sorting bridges are usually restricted to smallish specimens, say not greater than a few inches in diameter. They are, however, usually used as a 100% inspection check ; proof, by use, of their effectiveness. Aircraft and car parts tested include valve springs, valves, connecting rods and gudgeon pins. Frequently there is a direct relation between hardness and magnetic sorting bridge effect. Here, of course, the bridge is much quicker at "hardness testing" than the usual hardness test apparatus. The sample has merely to be put inside the coil, perhaps a slight adjustment of a control knob, and the C.R.O. trace observed and sample removed. The rate can easily be several pieces per minute.

The basic electronic circuit is a balanced four arm bridge in which the coils and sample form an inductance. Usually circuit details will be complex so that faults in any of three or four likely variables of the test specimen will give different visual effects, say different shapes on the C.R.O. screen. A typical case might be gudgeon pins tested for hardness and/or temper, but wherein one would very much like to get some special type of effect, say a rectangularity or double loop if the carbon content, or nickel, molybdenum alloying content varied from normal. Naturally some care is necessary in choosing the standard sample.

This form of n.d.t. is that most widely used in mass production in terms of number of parts tested, if not absolute mass, and is certainly the quickest and simplest to operate. It is much used in wartime, especially for small objects such as cannon shells.

Specialised coils using a form of the A.C. "skin effect" have been developed for fault detection in wires and sheets, particularly for cracks, laminations and stringers, even in non-magnetic metals such as aluminium, copper and brass (the good electrical conductors). For thin wire, such electro-inductive methods are almost the only suitable form of n.d.t. available.

CHAPTER 3.

ULTRASONIC METHODS.

One of the few early "crude" means of non-destructive testing which one can still see or hear in operation to-day is the ancient one of wheel tapping on railways. Since the method has been in use for about 100 years it seems not unfair to call it ancient, when contemplating, say, fluorescent liquids which have been used only since 1940. The wheel tapping principle is quite simply that an iron wheel vibrates at a distinctly different resonant frequency if it is pure, unflawed, from that when there is an appreciable crack in it. A tap from the linesman's hammer supplies energy which will normally cause the wheel to take on a complex mode of oscillation and emit a high, might one say, bell-like note. Any crack tends to give a very different type of oscillation due to its cutting off certain energy paths and prohibiting some modes of oscillation. The "timbre" of the note is altered and usually it is said a cracked wheel sounds hard or harsher.

Anyway, the expert wheel tapper still plies his trade and is usually credited with having saved thousands of lives from crashes which would otherwise have occurred from axle fatigue cracks, etc. This use of vibration or sound testing has been applied to a few other highly specialised situations—crudely by dropping small metal pieces and listening to their ringing note or making loose rivets oscillate until one can hear them. A rather neat application in the past was to bow, with a violin string, hardened turbine blades. A rise in pitch indicated correct, successful hardening—a lowered pitch told of fatigue cracks, usually at the blade roots, a dangerous position and hard to test. Sometimes electronic methods have been brought to help, using an oscilloscope as an aid, by seeing the wave envelope of the notes.

Normal wheel tapping with a light hammer is not altogether successful because at normal audible frequencies the wavelength of vibration is large compared with the crack size. Due to this, little energy is reflected by the crack, *i.e.*, only large cracks will be detectable. Stethoscopes have been co-opted from medical uses to aid detection but even with improved accuracy there is a feeling that the technique is not trustworthy, *i.e.*, insufficiently sensitive.

In air middle C has a frequency of 256 oscillations per second, corresponding to a wavelength of 130 cms. In steel a frequency of 20 kcs. gives 25·1 mm. as the wavelength and 1 mm. at 5 mcs., say 1/40th of an inch. Using the principle that the sound used should have a wavelength about the size of the crack detected, one concludes that the higher the frequency then the smaller the size of crack detected. The frequencies used in the n.d.t. methods to be described vary from ½ to 5 mcs. suitable to detect a crack of about 1/5th inch at 1 mc. (megacycle-million cycles per second).

The source of high frequency sound waves for n.d.t. purposes is either a piezo-electric or magneto-striction oscillator—almost invariably the former at present. Most humans cannot hear above 14 to 20 kcs. so the very high frequency sound waves are given a special name, usually "ultrasonics," sometimes "supersonics"—which latter is strictly incorrect. The ultra-sound from the oscillator is fed on to the test billet by suitable probes, the whole consisting of the transmitter. Usually the receiver is similar and both receiver and transmitter are connected to a C.R.O. circuit so that transmission and reflection pulses appear as "pips" on the same straight line.

Probes were initially flat, with the transmitting crystal parallel to the test metal surface. Then wedge shapes were used, the crystal being at, say, 30 degrees to the metal surface giving an angle beam suited to inspecting narrow blocks of metal and welds. This method is the most common at present, plain probes being restricted to deep metal, *e.g.*, large billets and blocks say at least a foot deep. The normal wedge probe seems to have a natural frequency of 1¼ mcs. For curved contours "perspex" plastic probe adapers are used—the plastic having several advantages.

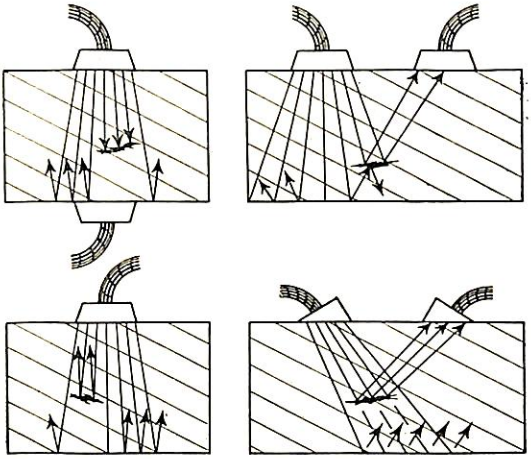
Ultrasonic methods for n.d.t. developed in Germany about 1931 using a rather poor liquid detector, travelled to England by 1941 and then on to America a year or so later where they have reached their greatest development. The early liquid detector relied on peculiarities seen in the interference pattern on the surface of the liquid, a somewhat crude method requiring considerable interpretation. A brilliant improvement on this, still used in Germany for lamination and flaw detection in wide sheet and strip, is a suspension of aluminium flakes in xylene. A rather clear image will then be seen of major flaws due to the aluminium flakes behaving as "Rayleigh discs" in the ultrasound beam. Where the beam has passed through the normal strip (source below the strip in the liquid tank), all the aluminium flakes set themselves perpendicular to the sound beam giving almost a mirror effect. Where, however, the beam has been reflected by lamination and its minute air gap, little or no beam is transmitted, and the aluminium flakes in the shadow will be randomly oriented—an easy visual pattern to see.

Perhaps one should mention here that ultrasonic n.d.t. is far better at detecting a flaw which has an air/metal surface, *i.e.*, a crack, than such things as inclusions and segregation. Ultrasound is strongly reflected at a metal/air interface—this has a further consequence that some trouble was met in early days getting all the beam or even a decent proportion of it into the metal. The normal air gap would be such a good reflector that most of the energy would be lost at the outer surface of the metal. For this reason a liquid is usually introduced between the probe and the metal, water, oil or patent fluids—liquids being extremely good ultra-sound conductors, eliminating the air gap.

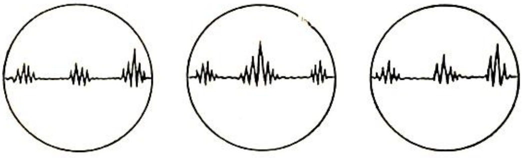
Usually then, detector and transmitter will be similar probes, occasionally the same one—the common American "transducer" technique where the one plate is both sender and receiver. The basic principle that a crack or any sudden discontinuity will reflect the ultrasonic beam can be used in several ways. Either one can detect the reflected beam—the usual English and American method—or one can detect the shadow at the far end, where there will be an absence of beam behind the flaw. As suggested above, shadow methods are used for strip and sheet, whereas for most other cases direct reflection is used.

Continuous oscillation is not used for ultrasonics. A development of radar is a popular principle. A pulse of waves is sent out of such a short duration that it has ceased being sent out before reflections from say ½" inside the metal have been received. This pulse and any reflections, including that from the far side or end of the metal are displayed on a cathode ray tube as in Fig. 2. The pulse is repeated as soon as the waves reflected from the far end of the billet have been received. Thus a continuous picture is seen on the screen consisting of a pulse at either end of a straight line—any "blips" in between indicating cracks or flaws.

ULTRASONIC FLAW TESTING METHODS



STANDARD PROBE POSITIONS



TYPICAL C.R.O. PATTERNS

Fig. 2.

In a typical display simple geometry will give the depth and approximate size of the crack. The ratio of the vertical heights of the flaw-pip and end boundary reflection pip will indicate the magnitude of the flaw. The ratio of the distances of these blips from the transmitted one will indicate the distance of the fault from the surface or far end.

The general method described above is similar to the Kelvin Hughes commercial apparatus sold in this country. It was developed from their renowned ultrasonic depth gauge instrument so widely used by ships for detecting the depth of the sea bed below them. A basically similar American equipment is the Sperry reflectoscope which claims to find sub-surface cracks, voids, ruptures, inclusions, piping, shrinkage cavities or flaking at depths up to 28 feet in iron, steel, aluminium, magnesium, bronze or brass. Copper has an unsuitable structure, *i.e.*, it either absorbs or scatters too much energy for ultrasonic n.d.t. Sperry's were the first to get grain size data in this way.

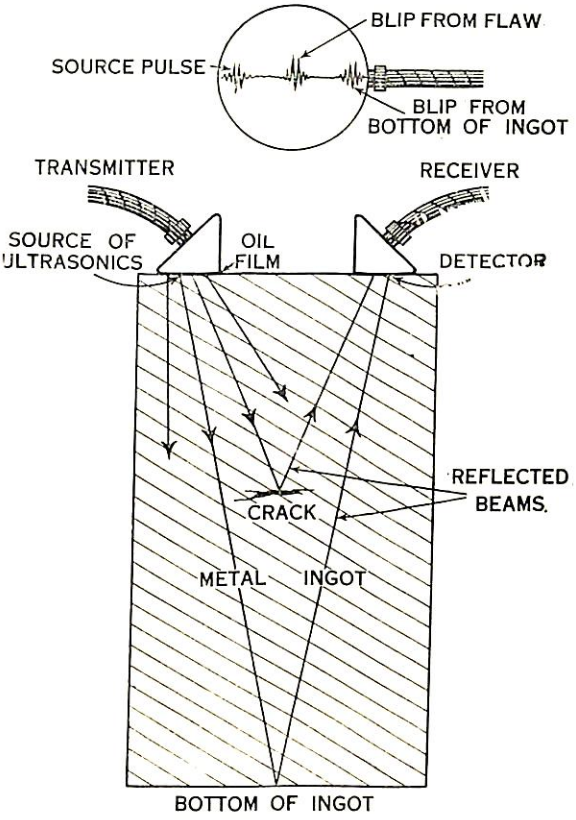


Fig. 3.

Sperry's use a quartz transmitter of $\frac{1}{2}$ to 1 sq. in. operating at 0·5 to 11 mcs. with oil as the contact liquid for fine, smooth surfaces and glycerine in water for rough ones. They claim to find a minimum defect diameter size of 0·1% of the distance traversed, say, ⅛″ in 10 feet to a positional accuracy of up to ⅛″. The actual size of a flaw can be determined by reducing the ultrasonic frequency until the fault blip just vanishes, and calculating the appropriate wavelength. It must be remembered that the wavelength will vary from metal to metal depending on the speed of sound in that metal. Some people have disputed Sperry's claim to detect flaws closer to the surface than ½″. Sperry's also make a "Thruray" apparatus of slightly different but limited application.

Another American equipment is the Brush "hypersonic"—which specialises in lamination detection in strip, plate and sheet. The strip being tested passes through a trough of water containing a line of transmitters across the strip width, with a line of detectors beneath. Any lamination or other flaw operates a painting device which marks the side of the strip parallel to the flaw. Later the strip mill crew can inspect the marked section and see the sort of flaw, or a bell or light can be operated by the machine so that visual inspection occurs while the strip is passing through. This technique is suited to mass production inspection and is unique as far as strip fault detection goes.

Methods depending on rather different principles such as attenuation, scattering, damping coefficient, natural resonant frequency, etc., using ultrasonics can detect general segregation, porosity, minute hair line cracks, etc. By and large, however, these techniques are research laboratory projects only, needing experienced and highly-skilled operators.

Using the radar reflection principle several points must be observed :—

(1) The contour of the probe must be closely the same as that of the test object, *i.e.*, flat for billets, slabs, sheets, yet curved with the appropriate curvature for round bars and billets.

(2) To get good contact the surface should be smooth, certainly free from loose scale and, ideally, machine ground.

(3) A liquid contact is essential between probe and test surface, the liquid being oil or water based.

Before considering typical defects detected by ultra-sound n.d.t. there is another, new, mode of inspection using a different screen presentation on the C.R.O. corresponding to what is called "B scope presentation" in radar. Here, instead of the reflection beam causing the time base to be deflected into a blip or pip it gives a brightening effect. Thus a sound casting will give a bright spot for the moment of transmission and the end boundary echo. Any flaws in an unsound sample will show up as intermediate bright spots.

If combined with mechanical traverse of the sample face by he probes a very full use is made of the C.R.O. screen and for photo-recording much less film is required. At the moment the technique is not very far advanced.

Clink in large steel blocks, internal cracks in forged alloy steels and lamination in thick plate are easily detected. The latter can usually be confirmed and delineated on the surface by subsequent magnetic methods. Flame cutting cracks on large steel blocks have been found, slag and cracks in various types of butt welds and porosity in castings. Thermal hair line cracks missing in correctly heat-treated metal, are easily detected in large blocks and hammer tups.

In rolled and forged material hair line and general internal cracks, segregates and piping have been observed. The former generally differ from the usual pattern as seen on the C.R.O., by the scattering along the path length through the bar. Also, if the specimen has circular symmetry, mere rotation often shows whether the flaw is a crack or not (the echo blip vanishes when the ultra-sound is parallel to the plane of the crack, a situation which does not arise in segregates and piping due to their not being planar).

Supersonic n.d.t. has even been applied to enable the incubation time from rolling to first appearance of flaw cracks to be found. It is suggested that after a 20 hours' delay steady development occurs for the next 50 hours. Hair line cracks have been found in forged discs when not detected by magnetic means. A few cases exist on both sides where magnetic or ultrasonic n.d.t. has succeeded where the other has failed, but they rarely conflict as the one is essentially an internal flaw detector and the other a near surface one.

Segregation and piping tests give good indication of the necessary discard or crop of ingots—worthwhile tests for large or expensive casts. In composite plate (mild and stainless steel for instance) welded together, areas of poor adhesion are detected as for lamination. With castings it is best to reduce the operating frequency as scattering tends to be high compared with rolled or forged material. Shrinkage cracks are detectable but frequently the cast structure is somewhat adverse to ultrasonic methods.

In deciding what frequency, etc., is to be used one must first decide the distance limits between which flaw detection is required, the minimum flaw size whose detection is needed and the length of the transmission leads. Scattering is approximately proportional to the frequency used and reduces sensitivity, but a high frequency is necessary to find small flaws. A great point about ultrasonic n.d.t. is its portability, needing only a suitable A.C. point for a plug-in, but if the lead lengths to the probes becomes excessive sensitivity is again reduced. Further, in general the method can be considered useless for material less than ½″ thick, but lengths up to 30 feet are acceptable. At a 2 mm. wavelength a $\frac{1}{32}$″ diameter hole will be detected at 8″. Non-metallic inclusions (sand, slag) do not reflect well and so tend to be invisible. Large shafts, forgings, billets of almost any size may be inspected but trouble can be met with if they are of any irregular shape, due to stray reflections from boundary walls.

In testing welds on large buildings—for instance the main girders of the Margam Abbey works, Wales—horizontal cracks and defects will be readily detected with sender and receiver probes a few inches apart on the same surface, but vertical flaws will be missed unless one is prepared and uses special techniques. Frequently, for working in the open, high up in awkward situations the probes are contained in permanent magnet clamps for easy manipulation.

By implication ultra-sound is used largely for steel, as so far mentioned. It has been found very useful in the light alloy field, aluminium for instance where frequently semi-skilled labour is used as opposed to the very technical viewers in the steel works and foundries. Extruded sections, so popular in aluminium, are, of course, ideally smooth and suitable for ultrasonics, but castings usually need a little initial grinding or machining prior to inspection. Lanolin or white spirit is the common transmitting liquid. Segregation, particularly of $MnAl_6$ can be detected.

The railways use ultrasonics for difficult axle testing. An example is the old L.M.S. which developed a method for finding transverse fatigue cracks in axles under the hub of press-fitted wheels—normally a nearly impossible feat without taking the axle and components to pieces. They also use it for testing butt welded rail joints and of course it universally replaces wheel tapping as a standard axle or wheel fatigue crack test in routine maintenance, except where magnetic techniques are easier or very near surface cracks are expected.

Summarising, ultrasonic n.d.t. uses a slightly complex apparatus which is very portable and excellent for crack detection deep inside forgings, blocks, billets, large welds, etc. There may be trouble with some castings, especially where patricularly adverse crystal structures occur. Detection of other types of flaw is less certain.

CHAPTER 4.

RADIOGRAPHY—THE X AND GAMMA RAY METHODS.

Radiography is probably the first technique which the layman may think of when he ponders about methods of non-destructive testing. It can be spectacular, searching for hidden defects in huge billets, forgings, castings, welded pressure boilers, etc. The object to be tested may be huge and the apparatus is neither small nor readily portable. Further, of course, it is one of the only two methods for deep internal flaw detection and was for a long time the only one.

The principles of radiography are similar to those for taking an X-ray photograph of one's chest. Needed are a source of rays, a detector and the specimen, of course. The rays are absorbed or scattered in proportion to the mass of specimen passed through. For specimens of uniform thickness, then the absorption of the rays will be proportional to the density. Most people will have seen this amply illustrated by mass radiography of the chest—an object of approximately uniform thickness but varying density. The bones are dense due to calcium and phosphorus, hence opaque to X-rays compared with the light flesh which tends to be transparent. Hence with suitable choice of X-ray source and detector a good internal photograph can be obtained with considerable contrast between the bones and flesh—and even flesh of different density, muscles, cartilage, ulcers, tumours, etc. If the object under test is not of uniform thickness the issue may be more complex, for a thin section of high density will have the same stopping power to the rays as a thick section of lower density.

Now radiography for medical purposes has a history of perhaps 50 years, for metallurgical n.d.t. not more than 25. Hence it is not surprising that the early techniques used for n.d.t. radiography were based on medical ones. Only recently have the needs of n.d.t. given rise to rather specialised equipment and methods. Of course the wealth of background information available from medical work helped the development of n.d.t. techniques immensely. Indeed, knowing the difficulties of cost, skilled technicians and interpretation, it is highly doubtful if X-ray methods would ever have developed for n.d.t. purposes had not they already existed in a medical form not very difficult to modify for metallurgical uses. As will be seen later, the contrast obtained in n.d.t. radiographs is much less than in medical ones—because only a small, or very small amount of flaw is present in a large or huge mass or high density material. The flaw may be a crack or hole of near zero density compared with say 7·8 or so of steel, or merely, say, 2·3 for a sand inclusion. To detect a small flaw clearly a very sensitive equipment is necessary. To take a hypothetical case, imagine a cast billet a foot thick, sand grains in it will not be greater than a tenth of an inch diameter at the very most. Looking through a section the X-ray beam is expected to detect the difference between 12″ of density, say 7·8, and 11·9″ of 7·8 plus 0·1 of 2·3. The total thickness times densities are 93·6 and 93·05—a difference of 0·55% requiring an accuracy of at least five parts in a thousand.

However, to come back to the apparatus required before considering its application in any detail, X or gamma rays may be used. Until extremely recently man was unable to generate gamma rays of even the lowest penetrating powers; now, using betatrons, this is just possible. The natural and man-made rays have substantially the same properties, they are both very short wavelength high intensity electro-magnetic waves. They are similar to light and ultra-violet waves, but extremely penetrating. Some of their properties are closely allied to those of normal light—in particular they cause fluorescence of certain materials and affect photographic plates and films in an extremely similar manner to light.

X-rays are generated by X-ray sets, the essential portion of which consists of a metal "target" hit by very high energy electrons. A small amount of the energy of the electrons is turned into X-rays when they hit the target, which is then the source of the X-rays. The vast majority of the energy of the electrons is however spent as heat, *i.e.*, the X-ray source is a wasteful and inefficient one creating a large amount of undesired heat and a small amount of the required rays—just as a normal pearl lamp creates large amounts of unwanted heat and a small amount of light. These processes are very inefficient but the best available.

The heat generated in an electric light bulb is usually less than 100 watts and is dissipated by gas conduction to the glass bulb and then away in the air by convection and radiation. With an X-ray set, however, several kilowatts are generated continuously. If this unrequited heat is not removed the target melts, so that in practice the metal source is water cooled. This is just one of many complications with X-ray generation equipment and the resulting apparatus has a host of minor accessories, water supply, high voltage H.T. transformers, rectifiers, relays, etc.

When a metal is struck by high voltage electrons, *i.e.*, at least 20 kv. ones, two sorts of X-rays are emitted. There is the so-called white radiation—or all frequencies below a certain limit—*i.e.*, all wavelengths above a certain limit. The name comes from the similarity to the white radiation emitted by a hot filament in a lamp bulb, which is emitting a mixture of all visible radiations. There is also one or a few X-ray wavelengths specific to the nature of the metal target and usually there is a large proportion of these characteristic wavelengths compared with any given wavelength in the white radiation.

The characteristic radiation is particularly useful as it consists entirely of one wavelength and hence is of uniform penetrating power. For this reason it is widely used for crystallography and also n.d.t. purposes. The white radiation may be the largest proportion of the X-ray output of the target, but it is spread over a large region of wavelengths each of which will have different penetrating powers and this leads to confusion in radiography. The particular wavelength of X-rays used is controlled by the pure-metal target, iron, molybdenum, cobalt, tungsten are typical metals used—and these targets can be substituted or exchanged in half-an-hour or so, the main delay being in recreating the vacuum after a new target has been inserted.

Hence, X-rays are generated when a metal stops electrons moving at high velocities. The electrons are created by thermionic emission inside a vacuum and accelerated by high potentials. For crystallography, voltages below 100 kv. may satisfy—for n.d.t. the limit has always been the available equipment—up to 2 mv. is now used—two million volts. A tube working at 250 to 400 kv., say, a quarter to half-a-million volts, will give rays suitable for inspecting 5″ thickness of steel. One of the chief disadvantages has been that as one increases the voltage so the current tends to decrease, *i.e.*, roughly the product of current times volts is constant. Now the voltage controls the penetrating power of the rays, but the current controls how many rays one gets. So the tendency has been that as one increased one's penetrating power one's beam intensity fell, *i.e.*, one's exposure time increased. Till the last five years or so there was no solution to this, and voltages above 500 kv. were rare to unobtainable.

So far one has mentioned only X-rays and the fact that modern Van de Graaff generators and betatrons, mostly used in America, can operate up to 2 mv. Now since the earth began, there have been natural sources of gamma rays up to and exceeding 2 mv. in penetrating power. These are the radio-active minerals and elements. Gamma rays are almost identical with X-rays but more penetrating, *i.e.*, developed by a source of higher operating voltage, so to speak. There is no clear line of demarcation between the two and X-rays generated by a betatron a 2mv. have identical properties to gamma rays of equivalent voltage from say, radium.

When the natural limit of X-ray sets was 500 mv. there were commercially available, radium concentrates giving off rays up to 2·2 mv. energy. These radium sources are still used, for they do not require the large amount of equipment needed for the high voltage apparatus. Indeed they just consist of a minute amount of highly radioactive salt in a metal capsule with surrounding lead shield. They have the utmost portability attainable. Ten years ago radio-active sources were the only means of testing really thick metal sections, say a foot or more thick ingot, billet or casting, of steel.

The main difficulty with the radium source was its low beam intensity. While the rays are immensely powerful as regards penetration there are not sufficient of them, so that the exposure time tends to be long, maybe hours. This difficulty could hardly be overcome and is more or less usual with high energy sources as mentioned above. Delightful in its ease of use the radium capsule would frequently be set at the centre of a circle of castings radiographing maybe a dozen or more at a time. All these ray sources give off rays in all directions.

The ultrasonic methods offer competition to the radium methods, but were non-existent pre-war. The third competitor to the radium capsules is a direct result of atomic piles. This is artificially radio-active cobalt—usually just called cobalt-60.

So there are a variety of possible X and gamma ray sources. The other point to consider is the matter of detection of the strength of a ray beam and its presentation in a suitable form, *i.e.*, a visual one. In practice only two methods are used, the photographic film, and the fluorescent screen. The former is somewhat more accurate, but slower, although it has the definite utility of giving a permanent record which can be inspected later in case of doubt or dispute. The fluorescent screen technique is rapid albeit of less sensitivity. It is still not as widely used as one would expect, for it is the only way to make X-ray inspection suitable for mass production techniques.

Almost all the radiographs one sees are photographic films, so it is worthwhile to consider the film in some detail as one can reach conclusions on its abilities and disadvantages. X-rays affect the silver salts in a photographic plate or film in just the same way as visible light. The density of the image obtained depends on the percentage of the X-ray beam which has reached the film, and, of course, on the amount of that beam which has been absorbed by the film, *i.e.*, the efficiency of the film as an X-ray detector.

As with visible light the image density is taken as the logarithm of the intensity of the incident beam on the film to that of the transmitted one. Thus a density of 1·0 implies that 90% of the X-ray beam is absorbed by the film which makes it a highly efficient detector. This film density can be varied by the manufacturer, a typical value being 0·7 although up to 2·0 is used in special cases. The actual intensity of the beam incident on the film depends on the absorbtion of the different regions in the casting or billet, etc., through which the beam has travelled.

A high contrast is necessary to detect minute defects. A typical graph of film density against log. of beam intensity is plotted in Fig. 4 and the degree of contrast obtained will be proportional to the slope of this curve, just as for ordinary light. In practice the film will be used on the straight line portion of the curve beyond a log. beam intensity of 1·8—beyond this point the contrast is constant and a maximum. (The beam intensity is determined by electronic methods).

Frequently the object being radiographed has varying thickness across its section, so that in order to obtain a film of approximately equal image density over all its surface the straight line portion of Fig. 4 must be used. In practice, then, when the object tested varies in thickness in the direction of X-ray penetration, contrast must be sacrificed to some extent for the sake of uniform density. When high contrast is quite essential, then small sections of equal thickness must be photographed on separate films with conditions so set for absolute maximum contrast.

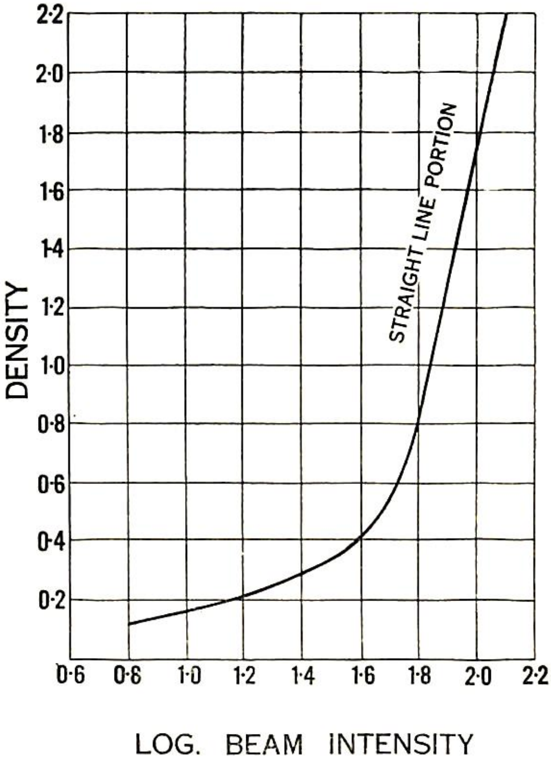


Fig. 4.

A peculiarity of X-ray films is that they are almost invariably double-coated. They have a layer of silver salts on both sides of the base—different from normal film. The two thicknesses give double the intensity of course, *i.e.*, much less exposure time. Further one always examines radiographs in the negative so to speak. Positives only occur in book reproduction, etc.

Other methods occur for shortening exposure time, perhaps the most obvious being the intensifying screen. Screens can be made containing minerals which fluoresce under X-ray excitation, typical coatings being calcium tungstate or zinc oxide. These screens can be put before, after or on both sides of the film and will intensify by a factor of 6 to 12.

Another variable is the film particle size. Large grain size gives greater speed, *i.e.*, less exposure time, at the expense of reduced contrast. Metal screens of lead foil are also commonly put in front of the film to filter out stray radiation, tending to increase fine detail detection and giving some intensifying effect, by a factor from 2 to 6 at 100/200 kv. (as for the fluorescent screens mentioned above).

To examine thick or dense metal sections a highly penetrating beam is required, generated by high voltage equipment. Contrast, is, however, in general less with increasing voltage, as well as exposure time. Compromise governed by experience is essential, a guiding rule being that an exposure of 1 to 10 minutes usually gives good results. Exposure charts are available giving the relation between thickness of specimen and exposure time to give equal film densities.

The major problem often unmentioned is that of scattered radiation. During its passage through a considerable thickness of metal a large proportion of the X-ray beam is "scattered" and becomes a nuisance as it raises the general background intensity of the film, reducing contrast. It causes fogging and is entirely a disadvantage. The ratio of scattered to direct radiation increases in proportion to the thickness of metal passed, for the direct beam is constantly being weakened and more scattered radiation formed. As an example, when steel 2¼" thick is being radiographed at 200 kv. the ratio of scattered to direct radiation at the film will be 10 to 1. At about this level of fogging, interpretation becomes difficult.

A standard action to take is the use of Potter-Bucky type grids. These are lead strips placed at an angle to the direct beam so as to absorb the scattered radiation. This grid is oscillated mechanically above and parallel to the film to give uniform coverage and prevent shadows of the grids themselves. Other anti-scatter devices include special films and the intensifying screens mentioned above.

Scattering is at its worst when irregular shapes are being radiographed. Various pastes can be applied to even the outline of such a casting but care is essential not to introduce apparent cavities in the paste interpreted as being in the metal. Perhaps one might mention here that great care is needed in developing the X-ray films as numerous defects can be obtained, all liable to misinterpretation, from simple things such as a very small blob of water splashed on the film.

Finally it is clear that a small crack is much more liable to detection when it lies perpendicular to the beam than along it. Thus radiographs will be taken in two directions at right angles unless flaws are expected along some preferred direction or one is only interested in those along certain axes. Further, the film must be close to the metal examined or else blurred outlines will result. The film is usually put, along with any intensifying screen, in an aluminium casette ("little box"), aluminium being nearly transparent to X-rays.

Examination of Castings.

Sooner or later a distinction is necessary between essentially detrimental flaws and those which are merely annoying. It is essential not to be unduly worried over trivial flaws shown up by very sensitive equipment.

Typical casting flaws detected by radiography include :—

(*a*) Those formed during the liquid stage, such as gas and blow holes, slag and sand inclusions, porosity and piping.

(*b*) Those of the solid state, *i.e.*, shrinkage cracks and cavities.

DATA FOR 150 K.V. X.RAY SET

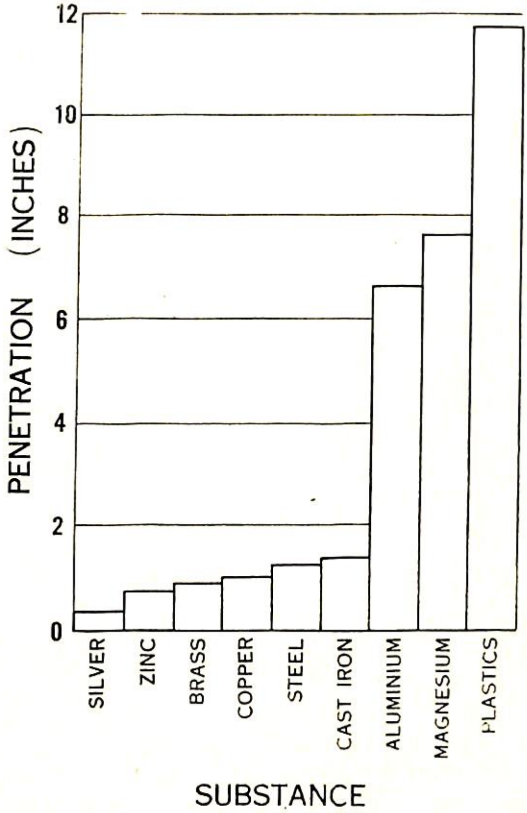


Fig. 5.

Slag and gas holes give a similar appearance in radiographs, merely circular, and having also the same mechanical effects on structure they need not be differentiated. Sand inclusions are often associated with cracking and hence considered dangerous. The cracks occur when the metal contracts on the incompressible sand grains. Piping and porosity do not spread during service and so are mostly unimportant ; in any case once detected they can usually be avoided by better foundry technique. A typical "set-up" for X-ray examination of castings is shown in Fig. 8.

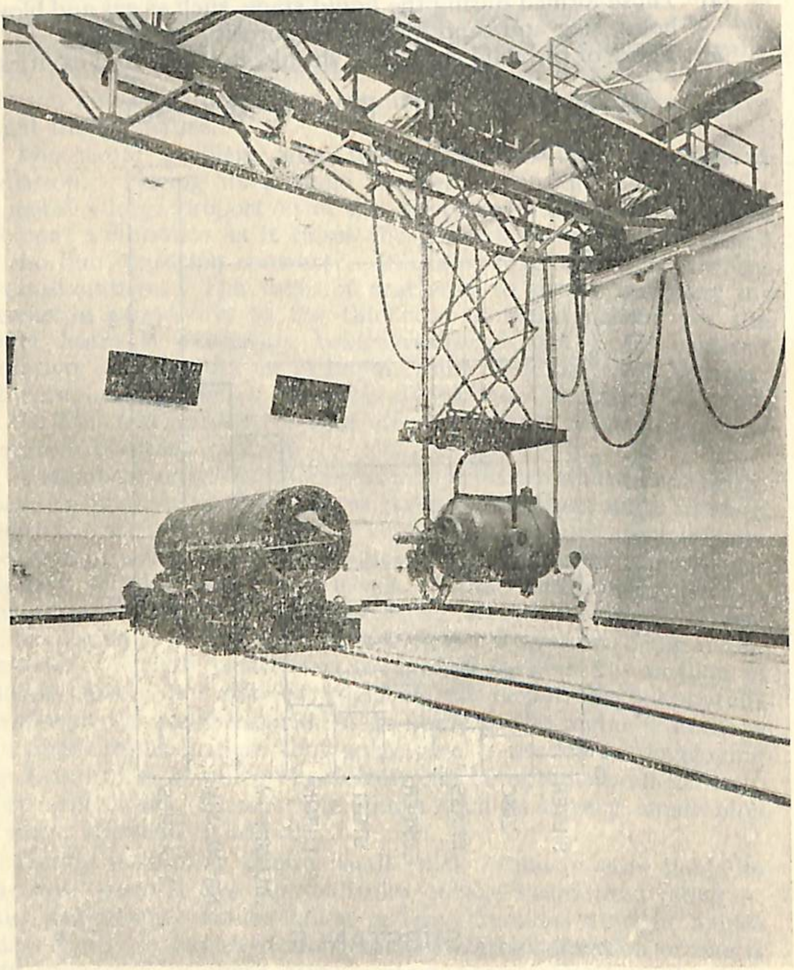


Fig. 6.

Piping and cracks may appear the same on a film, but the former does not change with direction of beam penetration. Shrinkage cracks are perhaps the major villains, because large stresses occur at their ends, tending to elongate them. Perversely they tend to be the most difficult to detect. Since cracks tend to "twist about" inside the metal usually one film detects most of them ; there will generally be a small section, at least, of each crack lying across the path of the penetrating beam.

Light alloys for aircraft construction come in for extensive radiography. Magnesium is generally accepted as being remarkably flaw-free whilst aluminium alloys tend to be porous, and generally a limit has to be set on the degree of porosity allowable. With these light alloys, visual examination with a fluorescent screen is common. It is much cheaper and quicker and girls can be trained for the job in place of specialist physicists. Although normally no record remains, the screen can be photographed, or even microphotographed if required. The screen is often viewed via a mirror at right angles as an added precaution against X-rays reaching the operator. Medical examination is desirable to ensure perfection in this respect.

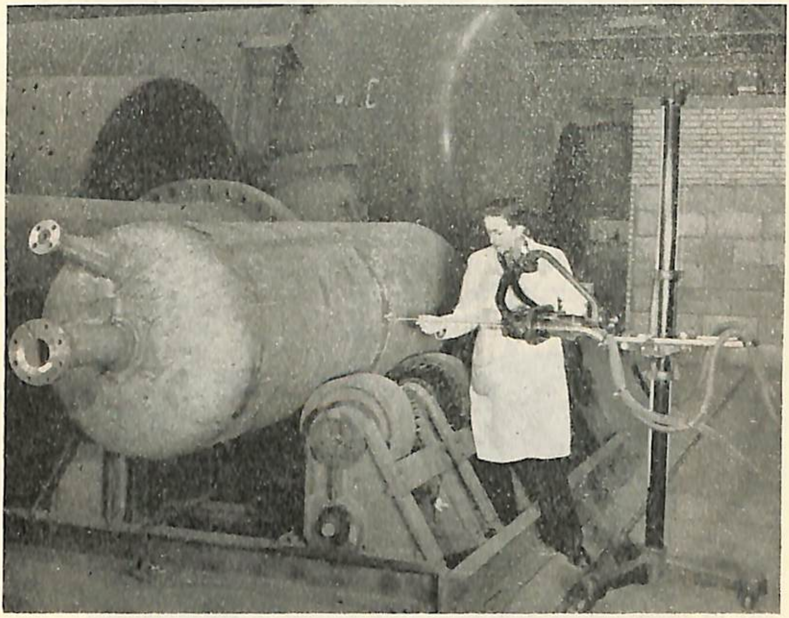


Fig. 7.

Fluorescent screens give less accuracy, the price for speed, especially regarding fine detail such as grain boundary segregation and minute flaws. Scattered radiation for light alloys is weak, one of the incidental reasons for the success of these visual methods.

Examination of Welds.

Some of the faults of welding which radiography can detect include :—

(1) Poor penetration—imperfect fusion.
(2) Slag inclusions.
(3) Shrinkage cracks of all types.
(4) Gas inclusions.

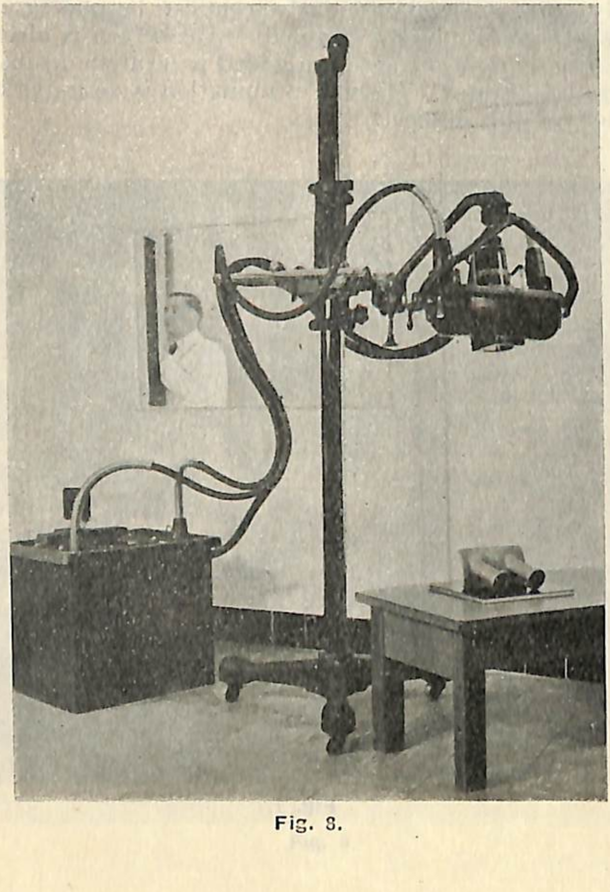


Fig. 8.

Again slag and gas inclusions are the easiest to detect. Incomplete penetration is often a serious defect but may be hard to detect, in which case it is best to direct the beam along the weld parallel to the scarfs. When even the most minute weld flaws are significant, every refinement in technique will be needed and ultimately flaws of as little as 1% of the weld thickness size may be observed.

To aid in this difficult detection of minute flaws, sets of standard wire or strips with varying size holes drilled in them may be examined under identical conditions or even on the same film. Thus a direct check on detection ability is obtained ; these jig devices are called penetrameters.

Very often radiographs help in selecting the most suitable weld conditions of electrode type, rate of feed, current density, etc. Sets of welds taken under varying conditions and observed by X-ray beams will lead to a rapid choice of the best method. In many cases X-ray examination is preferred during these development processes of a technique when not used on production runs once the best method has been determined. Figs. 6 and 7 show X-ray tests in progress on pressure vessels.

X-ray examination is not restricted to the welding shop or foundry. Portable equipment is used in the field for testing bridges, ships, pipe-lines, large pressure vessels *in situ*, etc. Steel up to 4″ thick can be penetrated, *i.e.*, quite large structures. With small objects of circular symmetry such as pipes, boilers and pressure vessels the film may be placed on the inside and the X-ray equipment outside. For large objects the portable equipment may be put inside and the X-ray equipment outside. For large objects the portable equipment may be put inside and the film outside. Another variation is to examine longitudinal welds in pipe by setting the film up along the whole length and then either running the X-ray set along the pipe, or traversing the pipe slowly in front of the set.

Determination of Position of Flaws.

The position of the flaws inside a metal under X-ray observation can be determined by several methods, including :—

(1) Moving the specimen and film parallel with each other in opposite directions during actual radiography when only one plane will remain sharply defined. The position of the flaw or plane of definition can be calculated from geometry and is determined by the relative speeds of the film and object and their distance apart. The variables will be altered until the flaw is sharply defined.

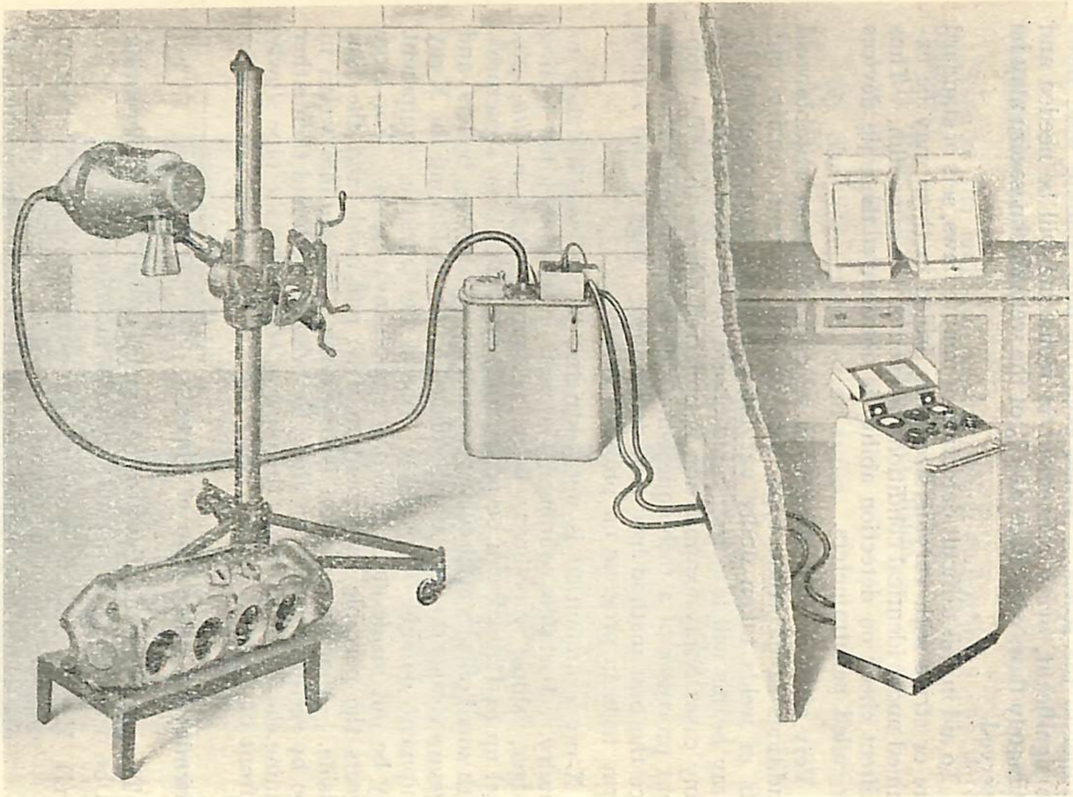


Fig. 9.

(2) Double exposure. Two photographs are taken at different angles ; from the geometry, image position, X-ray set, etc., the flaw position is deduced.

Other Applications of Radiographs.

Non-metals are far less dense for X-ray purposes and thus easier to inspect. Radiographs are commonly used during initial production and as an aid in development in plastics containing inserts, etc. A typical example is the defects which occurred when self insulating electric hot plates were found to burn out. Eventually the defect was traced to excessive bending of the spiral heater tubing leading to local overheating, arcing and burn out. Further, burn outs could be located and, if near the lead-in, were worth repairing and so radiographs giving the position of fault reduced the scrap percentage.

Ebonite, tufnol, corrugated cardboard, ceramics, abrasive bonded wheels, etc., are further examples of n.d.t. applied to non-metals for flaw detection. With fluorescent methods 100% inspection is carried out on some products such as spark plugs, electrical condensers, knots and cavities in wood, foreign bodies in food packets, cans, etc., telephone equipment, radio valves, oak beams (for death watch beetle). Soft woods are more transparent than hard, and dry wood less opaque than wet.

It is interesting to note that in the U.S.A. in 1931 there were 6 n.d.t. X-ray sets (5 of them used for castings), in 1936 they had 48 sets (16 for castings), by 1939 88 sets were used (31 for castings). The main objection to radiography other than mere conservatism was the high cost of film, *e.g.*, an aluminium producer in America in one factory was using 2100 sq. ft. of film a month, 90% of this for production development work.

For gamma ray work usually 200 mgms. of radium sulphate are used in a platinum capsule. Pre-war the U.S. Navy had 3000 mgms. of radium in 11 units for metal inspection in arsenals, etc., used for checking anchor shanks, shackle, pins, anchors, coupler knuckles, brass castings.

The modern radio-active source is cobalt-60 and it is interesting to compare its properties with radium. Radium has a half life of 1580 years and emits gamma rays of energy from 0·24 to 2·19 mv., an effective mean of 0·7 and an intensity of 2·5 curie units. Cobalt-60 has a half life of 5·3 years, emits rays of 1·18 and 1·33 mv., an effective mean of 1·21, with an intensity of 14·7 curies. So that it emits at two frequencies instead of seven, hence is more monochromatic, has a higher average penetrating power although its maximum is well below that of radium. In spite of an apparent too short half life its loss will be only 5% in six months. Like radium it is solid and stable chemically, usually kept in an aluminium container.

Fig. 5 shows the relative opacity of common metals to these rays. It has been said that a radiograph requiring an exposure of four hours at 1 mv. can be done in five minutes at 2 mv.

CHAPTER 5.

SUMMARY.

A convenient way of dividing the problems of non-destructive testing is to consider detection of surface flaws, and of those deep inside a large body of metal, say, at least ½″ below the surface. Surface methods will be magnetic particle method, wet or dry for magnetic materials, *i.e.*, most irons and steels, fluorescent liquid method for other metals. For deep internal flaws one can radiograph, using a film of fluorescent screen for detector, or ultrasonic methods can be employed. Both of these methods are more complex than the surface ones and it is useful to have standard defects to check one's equipment and interpretation from time to time.

In terms of cost, the fluorescent liquid method is cheapest, then the magnetic, then ultrasonic and X-ray. All forms are available in portable sets : the X-ray ones are usually large but substitution of gamma ray sources give extreme portability. In terms of flexibility the X-ray type will detect the greatest variety of different types of defect most certainly. Ultrasonic methods are largely restricted to crack detection and so are magnetic unless very skilful operators are used.

The fluorescent liquid technique is most direct and easiest for non-skilled people to use, then magnetic and ultrasonic.

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Photo-Credits.

Figs. 1-5. L. Manley.

Fig. 6. Messrs. Babcock & Wilcox, Ltd.

Fig. 7. Messrs. Newton Victor, Ltd.

Fig. 8. Messrs. Newton Victor, Ltd.

Fig. 9. Messrs. Philips Electrical, Ltd.

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23. 1″ ,, ,, ,, ,,
24. ¾″ Sq. Steel Tubes as Struts (30 ton yield).
25. ⅞″ ,, ,, ,, (30 ton yield).
26. 1″ ,, ,, ,, (30 ton yield).
27. ¾″ ,, ,, ,, (40 ton yield).
28. ⅞″ ,, ,, ,, (40 ton yield).
29. 1″ ,, ,, ,, (40 ton yield).
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31. Moments of Inertia of Built-up Sections (Instructions and Examples).
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33. Reinforced Concrete Slabs (Instructions and Examples)
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35. Screw Propeller Design (Sheet 1, Diameter Chart). } Connected.
36. ,, ,, ,, (Sheet 2, Pitch Chart).
37. ,, ,, ,, (Sheet 3, Notes and Examples)
38. Open Coil Conical Springs.
39. Close Coil Conical Springs.
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41. Metric Equivalents.
42. Useful Conversion Factors.
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44. Railway Vehicles on Curves.
46. Coned Plate Development.
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48. Solution of Triangles (Sheet 2, Oblique Angles).
49. Relation between Length, Linear Movement and Angular Movement of Lever (Diagram and Notes).
50. ,, ,, ,, ,, ,, ,, (Chart).
51. Helix Angle and Efficiency of Screws and Worms.
52. Approximate Radius of Gyration of Various Sections.

53. Helical Spring Graphs (Round Wire).
54. ,, ,, ,, (Round Wire). } Connected.
55. ,, ,, ,, (Square Wire).
56. Relative Value of Welds to Rivets.
58. Graphs for Strength of Rectangular Flat Plates of Uniform Thickness.
59. Graphs for Deflection of Rectangular Flat Plates of Uniform Thickness.
60. Moment of Resistance of Reinforced Concrete Beams.
61. Deflection of Leaf Spring.
62. Strength of Leaf Spring.
63. Chart Showing Relationship of Various Hardness Tests.
64. Shaft Horse Power and Proportions of Worm Gear.
65. Ring with Uniform Internal Load (Tangential Strain) } Connected.
66. Ring with Uniform Internal Load (Tangential Stress)
67. Hub Pressed on to Steel Shaft. (Maximum Tangential Stress at Bore of Hub).
68. Hub Pressed on to Steel Shaft. (Radial Gripping Pressure between Hub and Shaft).
69. Rotating Disc (Steel) Tangential Strain. } Connected.
70. ,, ,, ,, Stress.
71. Ring with Uniform External Load, Tangential Strain. } Connected.
72. ,, ,, ,, ,, ,, Stress.
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